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# APPLICATION OF STRAIN GAUGES IN MEASUREMENTS OF STRAIN DISTRIBUTION IN COMPLEX OBJECTS

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**Abstract**

This article presents an application of strain gauges in measurements of strain which occurs in charge air cooler during the thermal cycle test. The work shows the main idea of measuring system based on strain gauges and important aspects that should be considered when performing measurement. In this article there has been also presented construction and principle operation of a strain gauge measurement system.

**Key words:** strain gauge, FEA, charge air cooler, thermal cycle.

## 1 Introduction

Strain gauges measurements play an important role in many industrial sectors. Appropriate measurements systems can define the strain level occurring in different construction from biomechanics to civil engineering. Based on strain, life time and threat of specific construction can be calculated.

This article shows application of strain gauges in strain measurements for charge air cooler during thermal cycle test.

### 1.1 A Strain gauge

A Strain gauge (Figure 1) is a sensor used tomeasure strain. It has a conductive grid,which changes its electrical resistance when is deformed. Grid deformation is caused byforces coming fromloaded object to which strain gauge is mountedby bonding.Strain gauge produces as output change of resistance corresponding to a physical change of the investigated object.

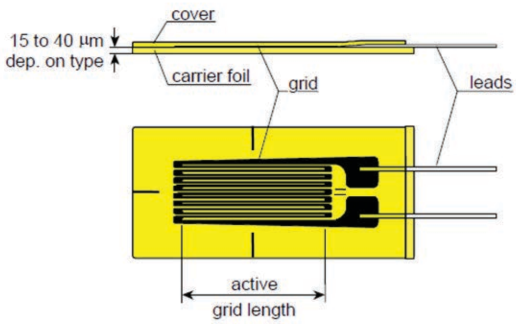


**Figure 1.** Stain gauge construction[www.hbm.com]

Functions of individual strain gauge's components presents Table 1.

**Table 1.** Strain gauge construction [own work]

| Strain gauge component | Function |
|---|---|
| Grid | strain measurement as change of resistance |
| Carrier foil | base for grid on investigated object |
| Cover | protection against pollution |
| Leads | connection with measuring device |

The strain gauge principle of operation is based on Equation (1). When the strain gauge is subjected to tensile or compressiveforces, itchanges its length and cross-section which affects change of the resistance.

$$R = \rho \frac{l}{S} \tag{1}$$

where:

R –electrical resistance [Ω]

$\rho$–electrical resistivity [Ω·m]

l – length [m]

s – cross section area[$m^2$]

The change of resistance is proportional to the change of the length, Equation (2).

$$\frac{\Delta R}{R} \sim \frac{\Delta L}{L_0} \tag{2}$$

where:

$\Delta L$ – diffrence between initial length $L_0$ and final L [m]

$L_0$ – initial length [m]

$\Delta R$ – change of resistance [Ω]

R – resistance [Ω]

The difference between absolute and relative change in length presents Fig. 2.

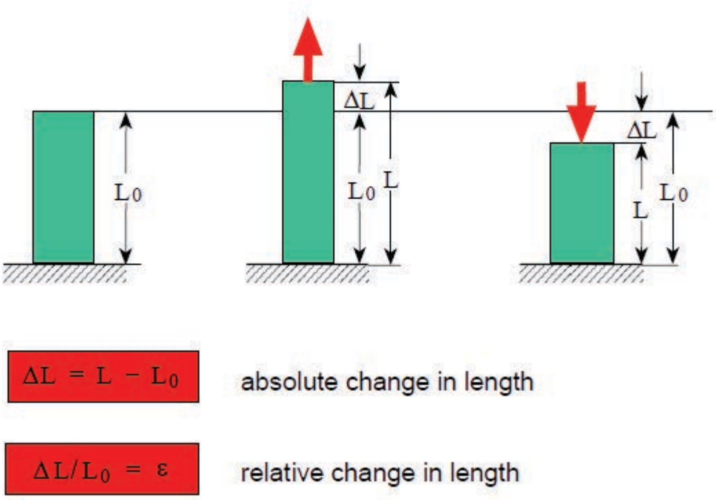


**Figure 2.** Absolute and relative length change[www.hbm.com]

Strain is the ratio of lenght change to the initial length of sample, Equation (3).

$$\varepsilon = \frac{\Delta L}{L_0} \tag{3}$$

Based on Equaition (2) and Equation (3) we obtain Equation (4).

$$\frac{\Delta R}{R} \sim \varepsilon \tag{4}$$

where:

$\varepsilon$ – strain [$\mu m/m$]

The proportional sign in Equation (4) can be replaced by a constant k, which is characteristic for the individual stain gauge and gives connection between resistance change and strain, Equation (5).

$$\frac{\Delta R}{R} = k \cdot \varepsilon \qquad (5)$$

Because$\Delta L$ is very small, the magnitude$10^{-6}\ m$ for strain εcommonlyused unit is $\mu m/m$.When selecting strain gauge following criteria should be taken in consideration:

- Material to which the strain gauge temperature response is matched
- Measuring grid resistance
- Maximum permissible effective bridge excitation voltage
- Number of measuring grid, their dimensions and positions to each other's

When the strain gauge has been selected, another important aspect is to use suitable adhesive and covering material adapted to working conditions, mainly in terms of the operating temperature. Figure 3 presents fully installed strain gauge on the object.

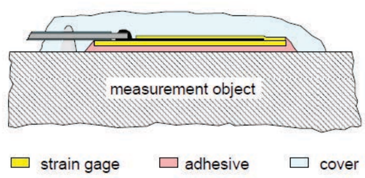


**Figure 3.** Properly installed strain gauge on object[www.hbm.com]

### 1.2 A Wheatstone bridge

A Wheatstone bridge (Fig.4) is an electrical circuit that consists of four resistive elements R1, R2, R3 and R4. On each of four legs of the Wheatstone bridgedepending on bridge configuration can be placed a resistor or a strain gauge which changes its electrical resistance when itis deformed by forces from the investigated object.

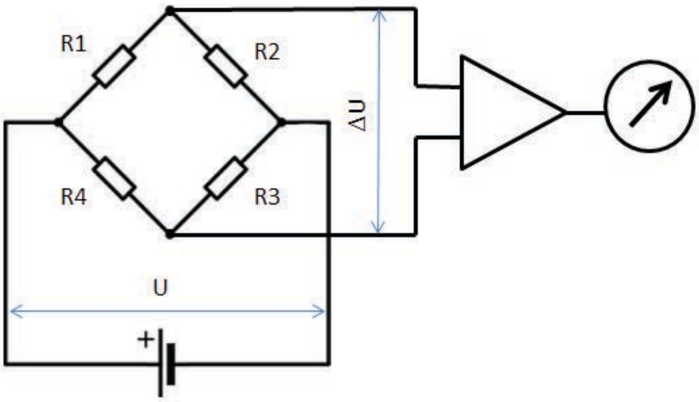


**Figure 4.** Wheatstone bridge circuit [own work]

The Wheatstone bridge works based on voltage division rule. Namely, in bridgethere are two parallel voltage divider circuits between nodes D and B: the first one is $R_1$ and $R_2$ and the second oneis $R_3$ and $R_4$. The output signal of Wheatstone bridge is measured between nodes A and C. Then the signal is amplifiedand recorded. By means of the Wheatstone bridge very small variations in resistance can be measuredon the level$10^{-4}\Omega$. The change in the resistance of Wheatstone bridge is calculated by measuring device as the strain. Strain can be positive (tensile) or negative (compressive). The magnitude of strain is very small that is why strain is often expressed as micro strain which means $10^{-6}$, instead of using commonexpression for this type of measurements for examplemm/mm.

The number of the active element in the Wheatstone bridge determines the kind of bridge configuration. There are three types of bridge configurations:

- quarter-bridge,
- half-bridge
- full-bridge.

Table 1 presents number of active strain gauge in each bridge configuration.

**Table 2.** Wheatstone bridge typedefinition [own work]

| Bridge configuration | Number of active Stain gauge |
|---|---|
| Quarter-bridge | 1 |
| Half-bridge | 2 |
| Full-bridge | 4 |

Fulland half bridge are used whenthe temperature compensation is needed. In case of half bridge there are 2 strain gauges. One is located in strain area and the second one is placed where is no strain. For both strain gauges the temperature must be the same in order that the second strain gauge could compensate impact of the temperature to strain measured by loaded the strain gauge.Similar, for full bridge configuration but there are 4 strain gauges. Two elements perpendicular to each other's in strain area and the others two in area where is no strain.It is possible also to compensate impact of temperature to strain in case of quarter bridge but a thermocouple is needed to record the temperature.

### 1.3 Wheatstone bridge for thermal cycle

In case of measurements connected with thermal cycle testthe bridge configuration is set as quarter with four wires strain gauge connection. Major strain in a charge air cooler is caused bytubes extension when the charge air temperature changes from lower to upper limit. Due to the time limitation, compensation of temperature was not included in the strain resultspresented in this article (Table 3) butthe calculated error on the level 5% is acceptable. However, the temperature was recorded and can be used to compensate the test results. Four wires stain gauges connection is used to compensate heat of the cables which ensuresbetter signal qualitythan two wires connection and eliminates potential noise.

## 2 Measuring sytem

Measuring system was based on HBM DeviceMGCplusAB22A (Fig.5)
The bridge was configured as quarter with four wires strain gauge connection. Four strain gaugesVishay SG 350Ohm WK-13-125BT-350 were used in the measurement.

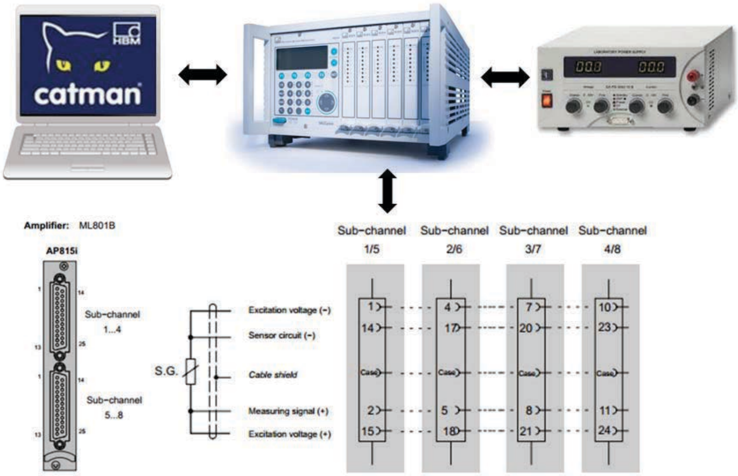


**Figure 5.** Measuring system[www.hbm.com]

All strain measurements were managed by CATMAN Easy software (Fig.6).

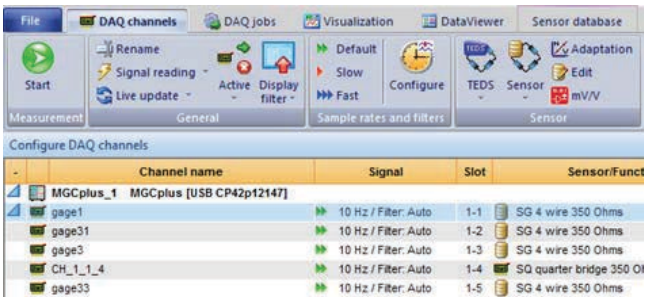


**Figure 6.** CATMAN Easy software[www.hbm.com]

The sampling frequency was set for 10 samples per second and the data was recorded for five minutes for each of stand configuration.

## 3 Measurement

The object of the strain measurements is a Charge Air Cooler (Fig.7).
It has an aluminum core that consists of set of tubes, cooling types called air centers, two reinforcements and headers. On the both ends of the exchanger

there are plastic tanks. Tightness of the system is ensured by gaskets placed between core and tanks.

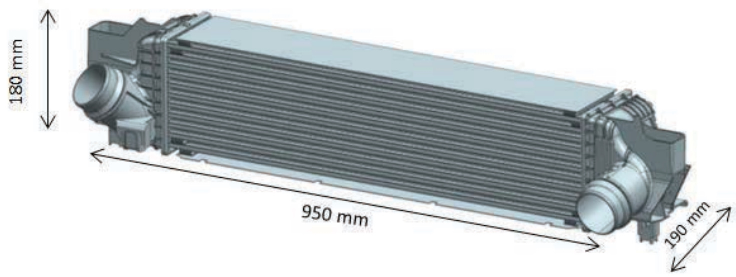


**Figure 7.** Charge air cooler [own work]

The aim of the measurement was to measure strain which occursin the charge air cooler's tubes with different parametersand configurations of the thermal cycle test stand (Fig.8).

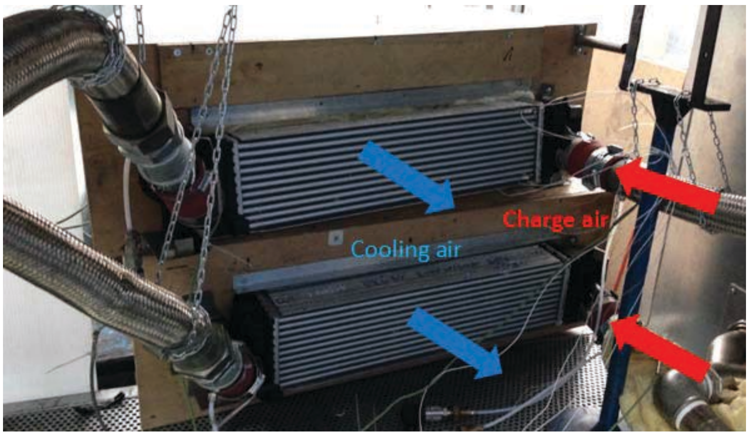


**Figure 8.** Thermal cycle test [own work]

The thermal cycle test relies on applying on the inlet side of the exchanger the charge air with specific flow, pressure and temperature changing in time. The another point of the test is cooling the core by external air.

Four stain gauges and thermocouples were glued on places where occurs the biggest stress level (Fig. 9).

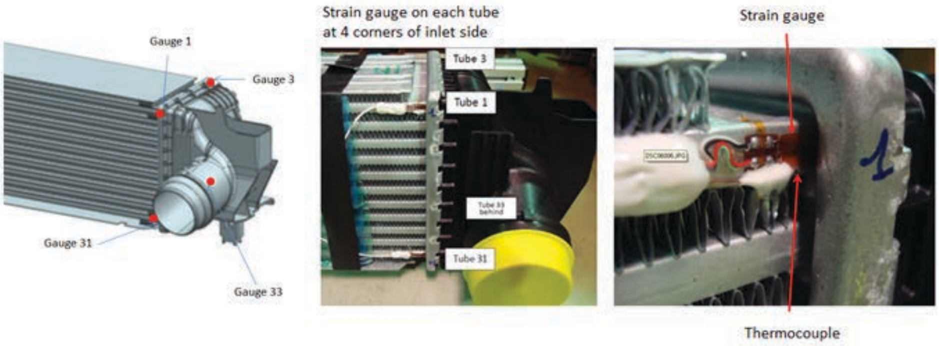


**Figure 9.** Strain gauge and thermocouples location [own work]

The exact position of sensors were definied by Finished Element Analysis. The most stressed  places of the charge air cooler are the four external tubes on the inlet side close to the header (Fig. 10).

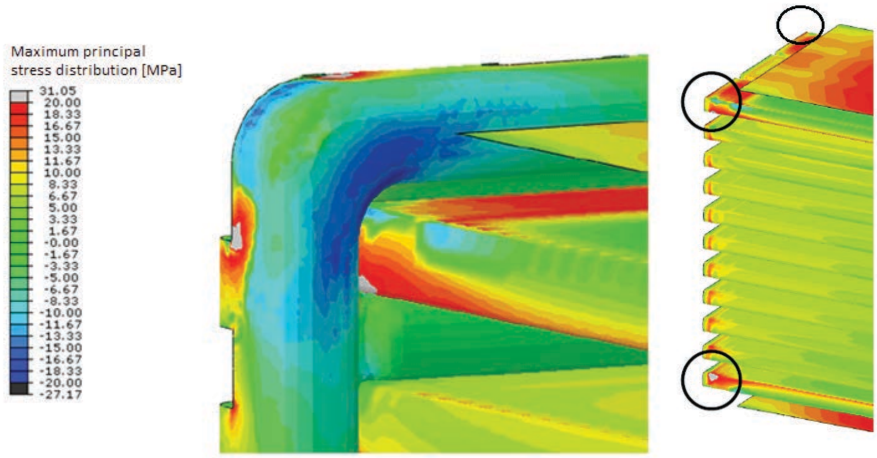


**Figure 10.** Maximum stressed places by FEA [own work]

Strain gauges measurements were done with different test parameters and test stand configuration (Table 3). During the measurements there was changed the maximum temperature of the charge air and ramp time which means the speed of the change of temperature from lower to upper limit. There were also changes of flow, external air speed and temperature. From stand configuration the size of the duct which provides external air has been also changed to supply cooling air on different area of the charge air cooler.

**Table 3.** Strain and temperature measurements [own work]

| Id | Internal Air | | | | External Air | | Measured magnitude strain [um/m] temp. [°C] | Gage3 | Gage33 | Gage31 | Gage1 | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Low temp. [°C] | High temp. [°C] | Ramp Time [s] | Flow [kg/h] | Temp. [°C] | Speed [m/s] | | | | | | |
| 1 | 30 | 220 | 30 | 600 | 20 | 8,1 | Strain | 563 | 635 | 922 | 475 | |
| | | | | | | | Temp. | 130 | 145 | 175 | 170 | |
| 2 | 30 | 220 | 30 | 600 | - | - | Strain | 908 | 1459 | 1054 | 569 | No external flow |
| | | | | | | | Temp. | 200 | 200 | 200 | 200 | |
| 3 | 30 | 220 | 30 | 600 | 20 | 8,1 | Strain | 715 | 649 | 794 | 507 | Shutdown flow during cold phase |
| | | | | | | | Temp. | 130 | 145 | 170 | 170 | |
| 4 | 30 | 220 | 30 | 600 | 24 | 10 | Strain | 584 | 529 | 685 | 454 | |
| | | | | | | | Temp. | 125 | 140 | 170 | 165 | |
| 5 | 30 | 190 | 30 | 600 | 20 | 8,1 | Strain | 540 | 560 | 755 | 410 | |
| | | | | | | | Temp. | 115 | 125 | 150 | 147 | |
| 6 | 30 | 160 | 30 | 600 | 20 | 8,1 | Strain | 452 | 438 | 570 | 374 | |
| | | | | | | | Temp. | 100 | 108 | 128 | 125 | |
| 7 | 30 | 220 | 30 | 440 | 20 | 8,1 | Strain | 533 | 458 | 716 | 407 | |
| | | | | | | | Temp. | 125 | 140 | 170 | 165 | |
| 8 | 30 | 220 | 6 | 440 | 20 | 8,1 | Strain | 529 | 376 | 763 | 476 | |
| | | | | | | | Temp. | 125 | 125 | 165 | 175 | |
| 9 | 30 | 190 | 6 | 440 | 20 | 8,1 | Strain | 472 | 344 | 678 | 438 | Passed real test |
| | | | | | | | Temp. | 110 | 110 | 140 | 150 | |
| 10 | 30 | 190 | 6 | 600 | 20 | 8,1 | Strain | 513 | 390 | 719 | 457 | |
| | | | | | | | Temp. | 115 | 115 | 150 | 160 | |
| 11 | 30 | 220 | 6 | 600 | 20 | 8,1 | Strain | 569 | 447 | 813 | 507 | Failed real test |
| | | | | | | | Temp. | 130 | 135 | 175 | 185 | |
| 12 | 30 | 220 | 6 | 600 | 20 | 10 | Strain | 549 | 433 | 746 | 485 | |
| | | | | | | | Temp. | 125 | 130 | 170 | 180 | |
| 13 | 30 | 220 | 6 | 600 | 20 | 5 | Strain | 631 | 589 | 895 | 543 | |
| | | | | | | | Temp. | 140 | 145 | 185 | 195 | |
| 14 | 30 | 220 | 6 | 600 | 35 | 8,1 | Strain | 548 | 447 | 763 | 497 | |
| | | | | | | | Temp. | 135 | 140 | 175 | 185 | |
| 15 | 30 | 220 | 6 | 600 | 35 | 10 | Strain | 518 | 444 | 716 | 474 | |
| | | | | | | | Temp. | 130 | 135 | 170 | 175 | |
| 16 | 30 | 220 | 6 | 600 | 35 | 12 | Strain | 788 | 839 | 838 | 576 | Small duct |
| | | | | | | | Temp. | 150 | 175 | 195 | 205 | |
| 17 | 30 | 220 | 6 | 600 | 35 | 10 | Strain | 758 | 840 | 828 | 582 | |
| | | | | | | | Temp. | 155 | 175 | 195 | 210 | |
| 18 | 30 | 220 | 6 | 600 | 20 | 10 | Strain | 744 | 812 | 809 | 551 | |
| | | | | | | | Temp. | 150 | 175 | 195 | 205 | |

From theTable 3 we can see that the main impact on the strain result is coming from external air and ramp time. Based on data from real test Table 3 we are able to identify what parameters have the biggest impact on the test result of the thermal cycle test for charge air cooler.

## 4 Conclusion

Correlation strain and stress from FEA with real measurements it is not easy task because the performed simulation is simplified versus the real test. However, the most stressed places pointed by FEA are in line with failure mode which occurs during the thermal cycle test. Therefore, this approach is correct to indicate where strain gauges should be glued and measurement should take place. The measurementsshow the strain level of the tubes and the influences of different test parameters to their strain level. Based on this information and realtestsdata we can define what test parameters have the biggest impact on the charge air cooler construction.

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